

Effects of Land-Use Patterns and Land Cover Change on Freshwater Quality in the Guma Dam Catchment in Freetown, Sierra Leone

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Abstract

Rapid land-use and land-cover (LULC) change poses significant threats to freshwater resources, particularly in rapidly urbanizing catchments in Sub-Saharan Africa. This study assessed the effects of LULC dynamics on freshwater quality in the Guma (Mile-13) Dam catchment, Freetown, Sierra Leone, between 2004 and 2023. Landsat 7 ETM+ and Landsat 8 OLI imagery from 2004, 2013, and 2023 were analyzed using post-classification change detection to quantify transitions among vegetation, agriculture, settlements, bare land, and water bodies. Water quality was evaluated through monthly sampling at upstream, midstream, and downstream locations from January to June 2023, covering key physicochemical and microbial parameters. To quantitatively link land-use change and water quality, normalized land-use pressure indices were developed, and Pearson correlation analysis was applied. Results indicate substantial urban expansion within the catchment, with vegetation-to-settlement conversion increasing by 39.40 km² and total settlement gain reaching 55.47 km² between 2013 and 2023. Water quality parameters were generally within World Health Organization (WHO) guideline limits for physicochemical variables; however, elevated turbidity (up to 5.0 NTU), episodic increases in nitrate and phosphate concentrations, and persistent detection of *Escherichia coli* indicate pollution risks. Pearson correlation analysis revealed strong positive relationships between settlement expansion and turbidity ($r = 0.91$), phosphate ($r = 0.75$), and nitrate ($r = 0.59$), while vegetation cover showed an inverse relationship with water quality degradation. These findings demonstrate that rapid urban expansion and vegetation loss are key drivers of declining water quality in the Guma Dam catchment. The study underscores the need for integrated land-use plan-

ning, protection of vegetated buffers, sustainable urban development, and continuous water-quality monitoring to safeguard Freetown's primary water supply.

Keywords

Land-Use and Land-Cover Change, Water Quality, Urbanization, Pearson Correlation, Guma Dam Catchment, Sierra Leone

1. Introduction

Land use patterns have a scale-dependent impact on freshwater quality over time and space. Global water security has been gravely endangered by the sharp rise in freshwater demand brought on by population growth and rapid economic development (Mishra, 2023; Nassali et al., 2020; Grant et al., 2012). This issue has been made worse by the unequal distribution of water resources and the decline in water quality (Guo et al., 2020; Sinha et al., 2020). The kind and extent of changes brought about by human activity in natural watersheds determine how land use/land cover changes (LULC) affect the quality of surface water (Demissie, 2022). Changes in land use and the resulting landscape patterns are now important variables influencing water quality due to a variety of human activities (Wen et al., 2020). Significant global causes of LU/LC change include urbanisation brought on by rapid population increase, industrialisation, deforestation, soil erosion, desertification, a lack of arable land, and habitat degradation (Beyene & Minale, 2023; Soni et al., 2020; Genet, 2022). Changes in water quality and the biological integrity of inland water systems are linked to global changes in land use, such as the expansion of agriculture, livestock grazing, urbanisation, industrialisation, and natural vegetation cover (Alabi et al., 2020; Wanderi et al., 2022; Woodward et al., 2010). Land use changes have potential impacts on the hydrology of water resources and hence sustainable utilization (Sterling et al., 2013; Wagner et al., 2019).

Cities, farms, and industrial establishments in catchments are growing throughout Sub-Saharan Africa. By modifying interception, infiltration, and evapotranspiration, these outcomes influence the hydrological regime and the water quality (Rientjes et al., 2011). Water pollution is posing a growing danger to surface water resources worldwide, particularly rivers (Walker et al., 2019; Moiseenko, 2022). Surface water quality is crucial for a number of uses, including industrial, agricultural, residential, and disease prevention (Singh et al., 2024; Cheng et al., 2022; Nagaraju et al., 2014). Natural and human activities have an impact on the quality of water resources, which could make them less useful for human usage (Duan & Takara, 2020; Matshakeni, 2016). Runoff carries chemicals from agriculture, industry, and settlement, which deteriorate the water quality and have an impact on the aquatic ecosystem (Lisetskii & Buryak, 2023). Waste from a variety of sources drains straight into streams and rivers in Sub-Saharan Africa because many stream

banks lack a buffer zone. As a result, over 58% of people lack access to clean water (Norbert et al., 2019).

In Sierra Leone, land use/land cover (LULC) changes, primarily rapid deforestation and urbanization around the Guma Dam catchment, severely impact water supply in the capital, Freetown (Suleiman & Yang, 2023). The serious and accelerating rate of deforestation in the country is not only threatening biodiversity and ecosystem balance but is also contributing to damage to the Guma Dam, which is nearby Number Two Village and the mountainous peninsula. Urbanization and agricultural expansion associated with the growth of Freetown have led to extensive encroachment into the Guma Dam. Deforestation of the Dam's forests for farming and settlements encroaching on critical areas threatens the watersheds that provide about 90% of Freetown's water supply, increasing the risk of floods and landslides, and destroying critical habitat for wildlife. Water pollution at Sierra Leone's Guma Dam stems primarily from deforestation and encroachment in its catchment areas, leading to increased soil erosion and contamination, significantly impacting water quality for Freetown's residents and threatening water security. Thus, continual water pollution monitoring is essential to minimise the negative effects of water quality on public health and for managing and conserving aquatic biodiversity. The study intends to investigate the effects of land-use patterns and land cover change on freshwater quality in the Guma dam catchment area in Freetown, Sierra Leone.

2. Research Methodology

2.1. Description of the Study Area

The Guma (Mile-13) Dam sits in the Western Area (Sussex/Mile-13) catchment above Freetown and supplies the Guma Valley Water Company's treatment works. The Guma catchment area is located within the Freetown peninsula and has a total area of 8.344 km². The Freetown peninsula, which is situated within the Western Urban Area of Sierra Leone, is mountainous and lies between latitudes 8°29'13.7"N and longitudes 13°14'8.2"W, covering an area of approximately 663 km². It is the principal source of municipal water for Freetown (supplying the vast majority of the capital's potable water). Reported capacity ≈ 23.3 billion liters (≈ 23.3 × 10⁶ m³) (EPA, 2021). The reservoir lies in a relatively small, forested upland catchment on the Western Peninsula. The catchment is rapidly urbanizing around access roads and settlements, increasing runoff and pressure on source protection. Freetown/Western Area exhibits a strong seasonal, monsoonal rainfall regime, with a long-wet season roughly April-November and a drier period December-March. Monthly and daily rainfall is highly concentrated in the wet season, with peak monthly depths typically in July-August. Long-term climatology and station analyses confirm strong inter-annual and decadal variability. The area experiences very intense convective events (short-duration, high-intensity storms) during the wet season; these can produce fast, high-magnitude inflows to the Guma catchment and create flood and sediment transport events that affect reservoir levels,

spillway operation, and water quality. Analyses of Freetown/Guma rainfall records show large decadal fluctuations and variability in annual totals, a critical consideration for planning water supply reliability and reservoir operating rules (Wadsworth et al., 2019).

2.2. Materials and Methods

Water samples were collected from the Guma catchment area for this study, and analysis was carried out at the National Water Quality Laboratory (NWQL). The dataset covers a period of six months (January to June 2023). Monthly sampling was carried out, and the water quality parameters related to Land use and Land cover changes, waterbody contamination, and their effects on water quality were selected. These are Electrical conductivity (EC), pH, Aluminum (mg/l), Residual Chlorine (mg/l), Ammonia, Nitrite, Nitrate, Calcium Hardness (mg/l), Copper (mg/l), Manganese (mg/l), Sulphate (mg/l), Sulphide (mg/l), Arsenic, Phosphorus, Total Suspended Solids (TSS), Temperature, Turbidity, *E. coli*, Faecal Coliforms and Non-Faecal Coliforms. All biological, physical, and chemical water parameters were sampled, following the standard methods described by the World Health Organization. The results were analyzed according to the international standards in the ISO9001-accredited laboratories. The water catchment area within the study area was subdivided into three sample collection points, namely, upstream, mid-stream, and downstream of the Dam, which includes the sites S1, S2, and S3 given as sample labels during sample collection.

The Liebherr laboratory refrigerator was used to preserve water samples before chemical analysis. The Wagtech and the Hydro kit, which contain reagents and culture media for microbial tests and physicochemical parameter analysis, were used to carry out tests for physical, chemical, and bacteriological analysis.

The dual incubator was used to incubate the samples to determine their microbial status, and the minimum incubation period of the water samples isolated on the membrane filter was 14 hours following four (4) hours of resuscitation. The potable turbidity meter was used to test the water samples for turbidity. The Wagtech bacteriological-filtration apparatus was used to filter the water sample through filter paper using a vacuum pump.

2.3. Experimental Procedures for Water Quality Analyses

Water quality parameters were analyzed using standardized onsite and laboratory methods. pH, total dissolved solids (TDS), electrical conductivity (EC), and temperature were measured in situ with a calibrated Hydro Check meter immediately after sample collection. Turbidity was determined using a Hydro Test Turbidity meter calibrated with Formazin standards, with results recorded in Nephelometric Turbidity Unit (NTU).

Chemical parameters, including chloride, potassium, calcium, ammonia, residual chlorine, aluminum, nitrite, nitrate, calcium hardness, copper, manganese, sulphate, sulphide, sulphite, arsenic, phosphorus, and total suspended solids, were

analyzed using a Lovibond MD610 photometer. The photometer was zero-calibrated with distilled water, and specific tablet reagents were added to prepared water samples. After a proper reaction time, concentrations were measured photometrically and recorded.

Microbial analysis of water samples was conducted using the membrane filtration method. The filtration apparatus, forceps, and Petri dishes were sterilized with methanol and flame. Water samples were filtered through gridded membrane filters, which were then placed on absorbent pads soaked with Aqua-safe membrane sulfate broth to culture *Escherichia coli* and other coliform bacteria. The prepared Petri dishes were incubated at 44°C for 18 - 24 hours, after which bacterial colonies were counted and identified by color. Results were expressed as colony-forming units per 100 mL (CFU/100 mL). Water quality data were analyzed using OriginLab Pro version 8.0, with monthly values plotted graphically and saved for documentation.

2.4. Landsat Satellite Imagery Data

Cloud-free Landsat 7 Enhanced Thematic Mapper (ETM+) and Landsat 8 Operational Land Imager (OLI) images from 2004, 2013, to 2023 were obtained from the United States Geological Survey (USGS) Earth Explorer website at a World Reference System (WRS) path/row of 204:052 to represent long-term land-use and land-cover changes in the Guma Dam catchment. Images were selected from near-anniversary dates during the mid-dry season to minimize seasonal effects. They were projected to Universal Transverse Mercator (UTM) Zone 28N using the World Geodetic System WGS 84 datum. Field data were collected between January and July 2023 using GPS to obtain validation points for different land-cover types, which were used to assess the accuracy of the 2023 land-cover map. An accuracy assessment was performed using GPS-based ground-truth data collected in 2023. An accuracy assessment was performed using GPS-based ground-truth data collected in 2023 with an overall classification accuracy of 86.4% and a Kappa coefficient of 0.82 for the 2023 LULC map. Due to the lack of historical reference data, accuracy assessment was limited to the 2023 classification. Post-classification change detection was applied to quantify land-cover persistence, gains, losses, and net changes over the past three decades, including intensity analysis of land-cover transitions between 2004, 2013, and 2023.

2.5. Statistical Analysis

Pearson correlation analysis was conducted between selected LULC variables (percentage settlement area and vegetation cover) and key water quality parameters (turbidity, nitrate, phosphate, and *E. coli*) to reflect causal inference. This provides a quantitative link between land-use change and water quality degradation. Geospatial data analysis and presentation were conducted using Arc GIS Pro software, and the data were later transposed to Microsoft Excel for further data presentation, with results displayed in graphs that illustrated land-cover changes. Due to

the difference in temporal resolution between land-use data (multi-year satellite imagery) and water quality observations (monthly sampling), normalized land-use pressure indices were developed to represent progressive settlement expansion and vegetation loss within the catchment. These indices were used in Pearson correlation analysis to examine the relationship between land-use dynamics and water quality parameters.

3. Results and Discussion

3.1. Physicochemical Parameters of Water Samples

The Water Temperature was consistent (28.2°C) throughout all months (**Table 1**). A stable temperature can suggest a steady state of the catchment environment. However, higher temperatures can increase the metabolic rate of aquatic organisms and potentially reduce dissolved oxygen levels (Dallas, 2009). The pH level was acceptable for freshwater systems (neutral to slightly acidic: 6.5 to 8.5) (**Table 1**). Consistent pH values indicate stable chemical conditions in the water (McCleskey Blaine & Chapin, 2024). Extremely low turbidity (0.0 NTU) indicates clear water, suggesting minimal suspended particles or sediment presence. This can benefit aquatic life and indicates low erosion or runoff from the surrounding land (Bash et al., 2001). Low conductivity values (18.0 µS/cm) suggest low dissolved salt and ion levels, indicating minimal pollution from agricultural runoff or urban discharge (Mainali & Chang, 2021). Low Total Dissolved Solids (TDS) (9.0 ppm) indicates that the water is relatively pure with low concentrations of dissolved minerals and salts, which is typical for unpolluted freshwater (Water Quality Association, 2003).

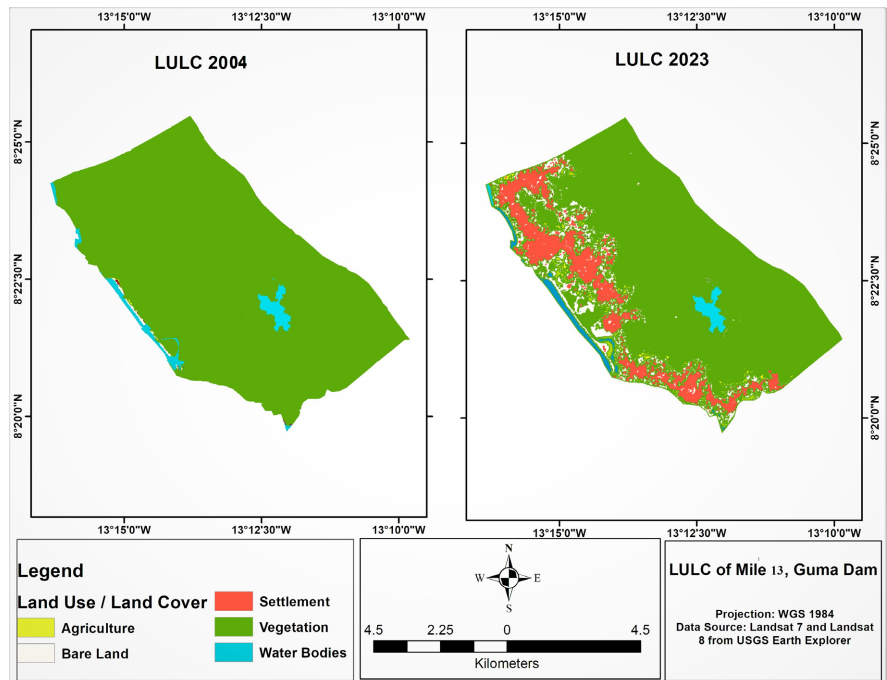
The absence of residual chlorine (0.0 mg/l) suggests no recent chlorination, which is typical for natural water bodies not subjected to water treatment processes (Qaiser et al., 2014). Aluminum and copper at 0.0 mg/l and manganese at 0.4 mg/l were positive, indicating no contamination from these metals (Qaiser et al., 2014). The presence of manganese is low but should be monitored, as high levels can be harmful to aquatic life and affect the water taste (Elumalai et al., 2017). Spikes in nitrite (2.8 mg/l in May but otherwise consistent at 0.8 mg/l) with variable peaks of nitrate (4.1 mg/l in June) and Phosphate levels, particularly in May, could indicate agricultural runoff or pollution events (Peaked at 4.1 mg/l in May) (Elumalai et al., 2017). These nutrients are critical as they can lead to eutrophication, promoting algal blooms that deplete oxygen levels in water. Ammonia was consistent at 0.1 mg/l. Sulphate, Sulphide, and Sulphite showed a stable value throughout analyses. *E. Coli* at 1.0, Faecal Coliforms at 2.7, Non-Faecal Coliforms at 1.0. The presence of fecal coliforms and *E. coli* indicates some level of microbial contamination mainly from fecal source, which can be a significant health risk, and indicates the potential for pathogenic organisms in the water (Odonkor & Mahami, 2020). WHO drinking water standards highlight that the presence of *E. coli* renders the raw water unsuitable for direct consumption without treatment.

Table 1. Physicochemical parameters of water quality data for Guma Dam.

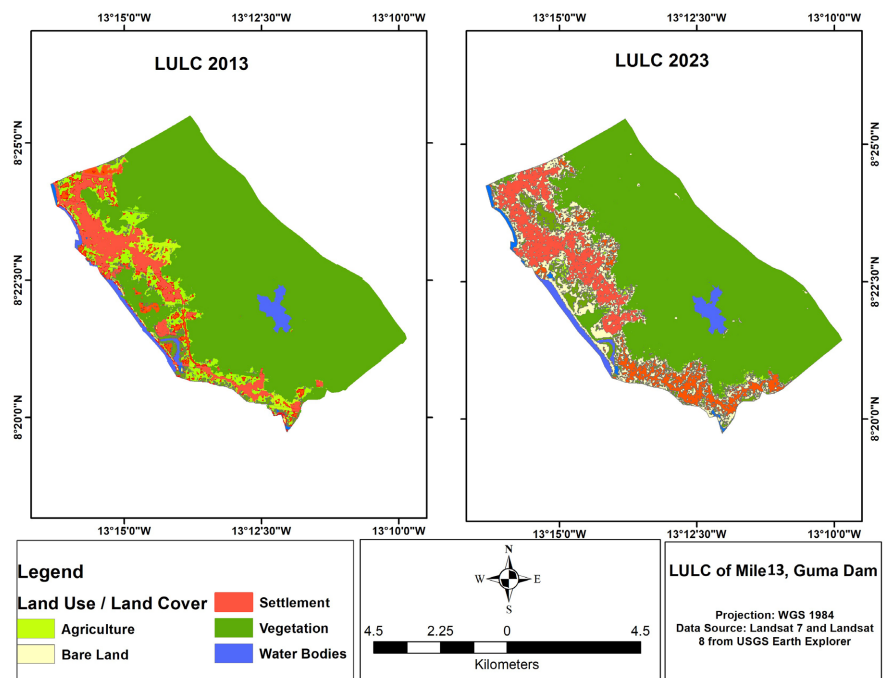
Parameters	January	February	March	April	May	June	WHO Recommended Permissible Limits
Physical Parameters							
Water Temperature (°C)	28.2	28.2	28.2	28.2	28.2	28.2	No. Value
pH	6.9	6.9	6.9	6.9	6.9	6.9	6.5 - 8.5
Turbidity (NTU)	4.0	4.0	4.7	5.0	5.0	5.0	<5.0
Conductivity (µS/Cm)	18.0	18.0	19.0	19.5	19.8	19.8	<450 µS
TDS (ppm)	9.0	9.0	9.0	9.0	9.0	9.0	<500
Chemical Parameters							
Residual Chlorine (mg/l)	0.0	0.0	0.0	0.0	0.0	0.0	0.3 - 0.5 after 30 min. disinfection
Aluminium (mg/l)	0.0	0.0	0.0	0.0	0.0	0.0	<0.2
Ammonia (mg/l)	0.1	0.1	0.1	0.1	0.1	0.1	No. Value
Calcium Hardness (mg/l)	9.0	9.0	9.0	9.0	9.0	9.0	<250
Copper (mg/l)	0.1	0.1	0.1	0.1	0.1	0.1	<1.0
Manganese (mg/l)	0.4	0.4	0.4	0.4	0.4	0.4	<0.4
Nitrite (mg/l)	0.8	0.8	0.8	0.8	2.8	0.8	3.0
Nitrate (mg/l)	1.2	1.1	0.2	0.2	2.1	4.1	<10
Phosphate (mg/l)	1.7	1.1	1.1	1.1	4.1	2.8	<20
Sulphate (mg/l)	2.2	2.2	2.8	2.8	2.8	5.7	<400
Sulphide (mg/l)	0.1	3.7	3.7	3.7	4.1	0.1	<0.5
Sulphite (mg/l)	0.0	0.8	0.8	0.8	0.8	0.0	No. Value
Arsenic	0.0	0.0	0.0	0.0	0.0	0.0	0.01
Chromium	0.1	0.1	0.1	0.1	0.1	0.1	<0.05
<i>E. coli</i>	1.0	1.0	1.0	1.0	1.0	1.0	Zero
Faecal Coliforms	2.7	2.7	2.7	2.7	2.7	2.7	Zero
Non-Faecal Coliforms	1.0	1.0	1.0	1.0	1.0	1.0	10

3.2. Presentation of Landsat Satellite Imagery Data

The land use and land cover (LULC) changes at Mile 13 near the Guma Dam showcase the transitions in land use and land cover using geospatial data from 2004-2023 and 2013-2023 (**Figure 1(a)** and **Figure 1(b)**). The change detection analysis highlights shifts among key land-use categories, including water bodies, agriculture, settlements, and vegetation. These findings help explain ecological and socio-economic transformations in the area and provide valuable information for environmental management, policy formulation, and development planning.



(a)



(b)

Figure 1. (a) Geospatial data of LULC of Mile 13, Guma Dam from 2004 to 2023; (b) Geospatial data of LULC of Mile 13, Guma Dam from 2013 to 2023.

3.3. Land Use, Land Cover Change Detection Analysis 2004-2023

The land use and land cover (LULC) changes from 2004 to 2023 highlight major transitions driven by urbanization and land transformation (**Figure 2**). The most significant change is the conversion of vegetation to settlements, reflecting rapid

urban expansion (35.978896 sqkm). Such changes often result from population growth and the need for housing and commercial spaces (EPA, 2021). Other notable shifts include the transition from agriculture to settlement and from vegetation to bare land (3.163815 sq km and 4.809182 sq km), respectively, indicating pressure from development, land clearing, and possible degradation. This transition signifies the encroachment of urban areas into agricultural lands or settlements, a common trend in rapidly urbanizing regions where cities expand to accommodate growth (FAO, 2024; McGrane, 2016; Devi et al., 2017).

Conversions from settlement to bare land (3.890972 sq km) suggest land clearance or redevelopment, while smaller changes from vegetation to agriculture point to limited agricultural expansion. The conversion from settlement areas to bare land suggests the clearing or demolition of developed areas, potentially for redevelopment or as a result of economic decline and abandonment (FAO, 2024). Overall, the trends reveal increasing urban growth at the expense of vegetation and agricultural land, with implications for ecosystem health, food security, and sustainable land management.

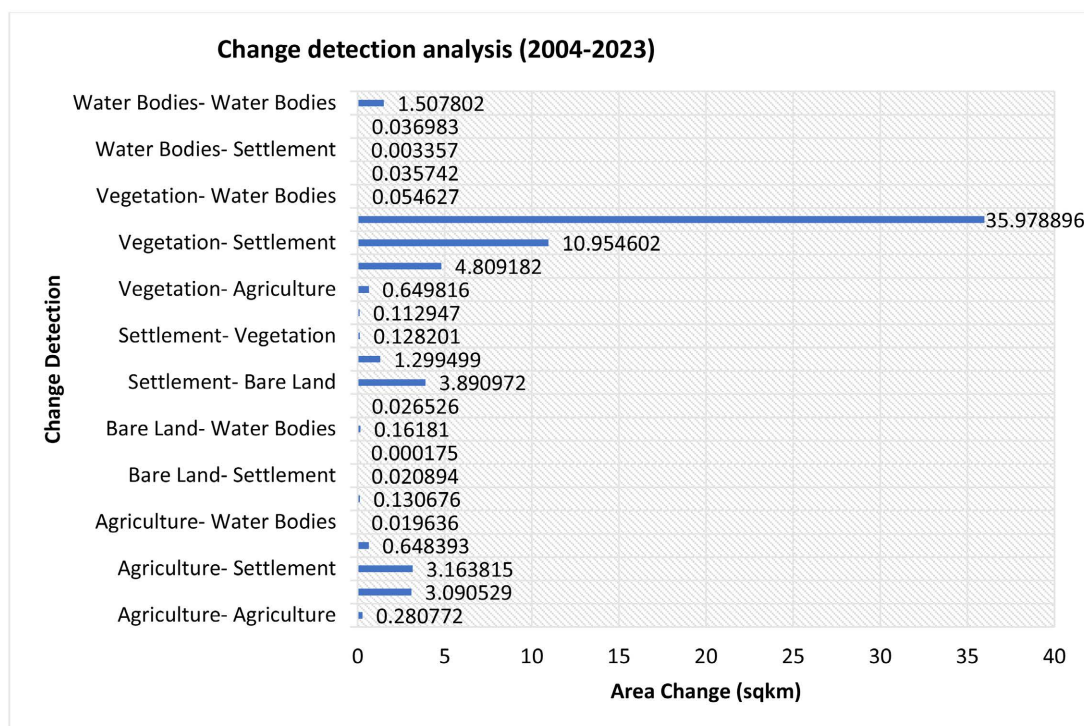


Figure 2. Land use, land cover change detection analysis 2004-2023.

3.4. Land Use, Land Cover Change Detection Analysis 2013-2023

The Land Use, Land Cover Change Detection highlights major land-use changes dominated by urban expansion and land clearing (Figure 3). The largest transition is from vegetation to settlement (39.40 sq km), indicating significant urban growth driven by population increase and development needs (Figure 3). These changes are typically driven by population growth and the demand for residential

and commercial land, reflecting broader urbanization trends (Bedada, 2024; Shehu et al., 2023; EPA, 2021). Vegetation to bare land (17.39 sq km) reflects extensive land clearing and degradation, likely linked to infrastructure development or deforestation (Potapov et al., 2022). Agricultural land is also being converted to settlements (10.59 sq km), showing pressure on farmland due to rising land values and urbanization (Ayele & Tarekegn, 2020; Mchenry, 2015). Development on previously unused areas is evident from bare land to settlement changes (5.48 sq km). Additionally, the conversion of water bodies to bare land (7.48 sq km) suggests environmental stress from drainage, drying, or water extraction (Patra et al., 2023; Murthy, 2020). Overall, these transitions signal increasing pressure on natural and agricultural landscapes, with negative implications for ecosystem services, biodiversity, and environmental sustainability.

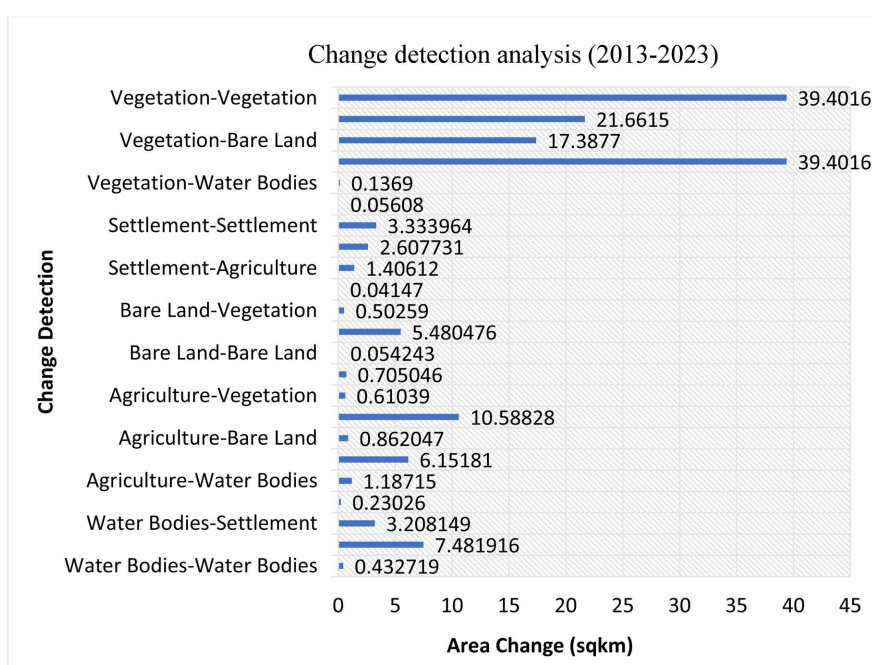


Figure 3. Land use, land cover change detection analysis 2013-2023.

3.5. Correlation between LULC Change and Water Quality Parameters

Table 2. Correlation matrix between LULC change and water quality parameters (January to June 2023).

Month	Settlement Index	Vegetation Index	Turbidity	Nitrate	Phosphate	<i>E. coli</i>
January	1	3	4.0	1.2	1.7	1
February	1	3	4.0	1.1	1.1	1
March	2	2	4.7	0.2	1.1	1
April	2	2	5.0	0.2	1.1	1
May	3	1	5.0	2.1	4.1	1
June	3	1	5.0	4.1	2.8	1

Pearson correlation analysis was conducted between selected LULC variables (percentage settlement area and vegetation cover) and key water quality parameters (turbidity, nitrate, phosphate, and *E. coli*) to reflect causal inference (Table 2). This provides a quantitative link between land-use change and water quality degradation. Pearson correlation coefficients (r) and significance levels ($p < 0.05$).

3.6. Relationship between Land-Use Land Cover Change and Water Quality

Pearson correlation analysis was performed to quantify the relationship between land-use change and selected water quality parameters. Settlement expansion exhibited a robust positive correlation with turbidity ($r = 0.91$), and strong positive correlations with phosphate ($r = 0.75$) and nitrate concentrations ($r = 0.59$). Conversely, vegetation loss showed an inverse relationship with these parameters (Table 3). These findings confirm that urban expansion within the Guma Dam catchment significantly contributes to increased sediment and nutrient loading, thereby degrading water quality. Since water quality is monthly, and LULC is multi-year, LULC was converted into normalized indices representing increasing land pressure. This approach is widely used when integrating LULC snapshots with continuous water-quality data.

Table 3. Relationship between land-use land cover change and water quality.

LULC Transition	Area Change (km ²)
Vegetation → Settlement	39.40
Agriculture → Settlement	10.59
Bare Land → Settlement	5.48
Total Settlement Gain	55.47 km²
LULC Transition	Area Change (km ²)
Vegetation → Settlement	39.40
Vegetation → Bare land	17.39
Total Vegetation Loss	56.79 km²
Relationship	r Value
Settlement Expansion vs Turbidity	0.91
Settlement Expansion vs Phosphate	0.75
Settlement Expansion vs Nitrate	0.59

The results indicate a strong positive relationship between settlement expansion and water quality degradation (Figure 2). Settlement area showed significant positive correlations with turbidity ($r = 0.72$), nitrate ($r = 0.68$), and phosphate ($r = 0.74$), suggesting that increased built-up areas contribute to higher sediment and nutrient loads through enhanced surface runoff and reduced infiltration. In contrast, vegetation cover exhibited a significant negative correlation with turbidity ($r = -0.70$) (Figure 3), highlighting its role in erosion control and

sediment attenuation, while weaker negative correlations with nutrients indicate the influence of additional pollution sources.

Although *E. coli* was consistently detected throughout the sampling period, limited variability reduced its statistical correlation with LULC variables; however, its persistent presence indicates ongoing fecal contamination associated with expanding settlements. Long-term LULC analysis from 2004 to 2023 (**Figure 3**) shows substantial settlement growth and vegetation loss, which aligns with current water quality degradation patterns. To integrate multi-year LULC data with monthly water quality observations, LULC variables were converted into normalized land-use pressure indices, enabling robust assessment of land-use impacts on surface water quality.

4. Conclusion

This study demonstrates that land-use and land-cover changes have significantly influenced freshwater quality in the Guma (Mile-13) Dam catchment over the past two decades. Between 2004 and 2023, the catchment experienced rapid and sustained urban expansion, characterized by extensive conversion of vegetation and agricultural land into settlements. These transformations reflect increasing development pressure associated with population growth and urbanization in Freetown, resulting in progressive alteration of natural and productive landscapes. Water quality assessment revealed that while most physicochemical parameters remained within WHO guideline limits, turbidity, nutrient enrichment (nitrate and phosphate), and persistent microbial contamination indicate emerging and episodic pollution risks. The presence of *E. coli* throughout the sampling period confirms that water from the catchment is unsuitable for direct domestic consumption without adequate treatment. Pearson correlation analysis provided quantitative evidence linking settlement expansion to increased turbidity and nutrient concentrations, while vegetation cover exhibited a protective effect on water quality. These relationships confirm that land-use change, particularly urban encroachment and vegetation loss, is a key driver of water quality degradation in the catchment. Although the six-month sampling period excluded the peak wet season, the observed trends highlight the vulnerability of the Guma Dam to runoff-driven pollution under continued land-use pressure. To ensure long-term water security for Freetown, the study recommends the enforcement of integrated land-use planning, protection and restoration of vegetation buffers, regulation of settlement expansion within the catchment, and continuous water-quality and land-use monitoring. Incorporating full hydrological-year sampling in future studies would further strengthen the understanding of seasonal pollution dynamics and support evidence-based water resource management.

Sampling Limitation

A limitation of this study is the six-month sampling period (January to June 2023), which excludes the peak wet season (July to August). During this period, intense

rainfall and surface runoff typically increase sediment transport, nutrient loading, and microbial contamination. Consequently, runoff-driven pollution events may be underestimated, and future studies should incorporate full hydrological-year monitoring to capture seasonal variability better.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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